Mean transverse momenta correlations in hadron-hadron collisions in MC toy model with repulsing strings

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Abstract. In the present work, Monte-Carlo toy model with repulsing quark-gluon strings in hadron-hadron collisions is described. String repulsion creates transverse boosts for the string decay products, giving modifications of observables. As an example, long-range correlations between mean transverse momenta of particles in two observation windows are studied in MC toy simulation of the heavy-ion collisions.

INTRODUCTION

Interactions between quark-gluon strings in hadron-hadron collisions are the topic of interest for many years. The models of such interactions, however, are mostly phenomenological. For instance, the string fusion model was proposed in [1, 2, 3]. It was shown that the string fusion phenomenon should lead to modifications of event multiplicity, transverse momentum spectrum, and to other consequences. The string fusion scenario was implemented in a number of MC models of hadron-hadron collisions [4, 5].

In [6], an attraction and a repulsion of chromoelectric tubes in hadron-hadron collisions is discussed. It is shown, that such interactions should lead to azimuthal asymmetry in the distribution of secondary particles. The following picture is considered:

1. quark-gluon tubes (strings) have a finite radius.
2. depending on the transverse distance between them, strings may overlap and interact.
3. strings attract or repel each other in the transverse direction.

In the first part of this proceeding, the toy MC model based on ideas from [6] is described. The motivation for development of such a model comes, for instance, from the results of dihadron correlations measured in Au-Au collisions in STAR [7], where patterns of the collective behavior are observed and a detailed fit of the correlation structures was developed. It is interesting to see what would be the "collectivity" in the frame of the toy MC model with repulsion strings. In the second part of the current proceeding, the so-called mean transverse momentum correlations are extracted from the toy model events. This observable may be useful to disentangle between string interaction scenarios, for example, between the string repulsion and the string fusion. Dihadron analysis of the MC toy model data is presented in the same proceedings [9].

MONTE-CARLO TOY MODEL

In this section a Monte-Carlo (MC) toy model with repulsing strings is described. The MC model is applicable to different types of hadron-hadron collisions (pp, AA, pA, etc.).

Stage 1. Simulation of hadron-hadron collisions, strings formation.
In this MC model, initial positions of the nucleons in nuclei are generated in accordance to Woods-Saxon distribution (for the Pb^{208}, the WS radius is 6.62 fm and parameter $a = 0.546$ fm). Nucleon core effect is not taken into account to speed-up computations. Inside each nucleon, some number of partons is distributed in transverse (xy) plane with 2D-Gauss law, with $\sigma_{xy} = 0.4$ fm. The *mean number of partons $n_{partons}$* inside nucleons is dependent on a collision energy and is a model parameter. Interaction between colliding hadrons is implemented at the partonic level: partons

can interact and form a *string*, if the distance between partons in *xy* plane is less then some *parton interaction distance* d_p. There is a 3% probability for a string to be "hard scattered" (this number is also a model parameter) – this is used for jets and jet-like structures simulation. All other strings are considered to be "soft" and "long" in rapidity, occupying rapidity range $y \in (-4, 4)$. As the result of this model stage, a configuration of strings appears. Parameters of the MC model are given in Table 1.

If at least one parton of the nucleon has interacted, this nucleon is considered as nucleon-participant. Fig. 1 shows mean number of nucleons-participants, nucleon-nucleon collisions and average number of produced strings as a function of impact parameter. One can recognize similar dependences in (nucleon-level) Glauber MC calculations.
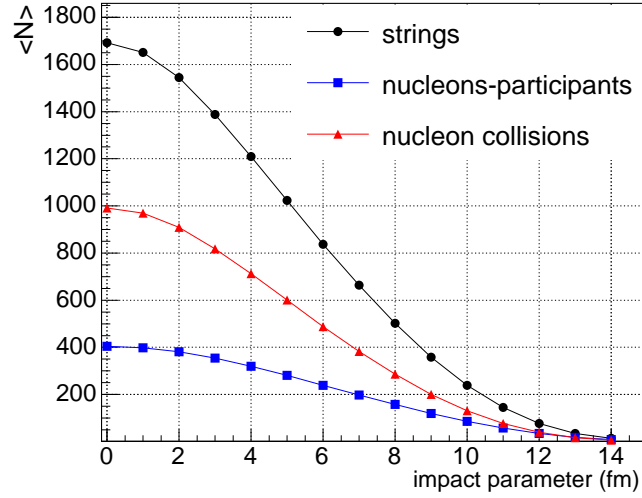

FIGURE 1. Dependence of the mean numbers of nucleons-participants, nucleon-nucleon collisions and strings on impact parameter in the toy model.

TABLE 1. Parameters of the MC toy model.

Parameter	Notation	Values		
average number of partons	$\langle n_p \rangle$	15		
parton interaction *xy* distance	$d_p = 2r_p$	0.4 fm		
string energy density	λ	1.0 GeV		
string radius	R_{string}	0.25 fm	1 fm	2 fm
string overlap energy density	λ_1	0.2 GeV	0.002	0.0001 GeV

Stage 2. Repulsion of the strings.

At the next step of the system evolution, "soft" strings interact with each other. In the current MC model, interaction manifests itself as a repulsion. The following repulsion mechanism is considered [6]. Each string has some *effective interaction radius* R_{string}, with corresponding string *effective transverse area* $S_{\text{string}} = \pi R_{\text{string}}^2$. A string which is far apart from the others has energy density per unit length λ. Two completely overlapped strings have energy density $2\lambda + 2\lambda_1$, while density of partial overlapping is $2\lambda + 2\lambda_1 \cdot S/S_{\text{string}}$, where S is the area of the overlap (i.e. it is assumed that effectively strings are "black discs" in the transverse plane). Here λ_1 is the energy density excess due to overlapping. When two strings interact in such a way, each string acquires transverse momentum

$$p_{\text{T string}} = l\sqrt{(\lambda + \lambda_1 S/S_{\text{string}})^2 - \lambda^2} \, . \tag{1}$$

After vector sum of all instantaneous momentum kicks, a string gains corresponding transverse relativistic boost $\vec{\beta}_{\text{string}}$. For different values of the model parameter R_{string}, λ_1 is manually adjusted in such a way that event-averaged string boost $\langle \beta_{\text{string}} \rangle \approx 0.65$ keeps constant in the most central collisions (this value is arbitrary chosen).

Doubled string radius $2R_{\text{string}}$ can be interpreted as the effective interaction distance between strings in the transverse plane. For example, it may be understood as a "mean path" of the string before it hadronizes.

At this stage of the event evolution, before hadronization of the strings, some figures can be plotted in order to understand the model behavior. Fig. 2 shows cartoons for peripheral (left) and central (right) events. Colliding nuclei and the structures inside them are in red for one nucleus and in black colors for the second. Nucleons are shown as large circles, smaller circles inside illustrate partons (the radii of the circles reflect the actual model parameterization). Blue full circles denote positions of the strings, and each green arrow shows the direction and magnitude of the gained Lorentz boost for one string (some threshold on minimum arrow length is applied in order to hide too short arrows). Red full circles are for "hard scattered" strings, which do not participate in the repulsion calculation.
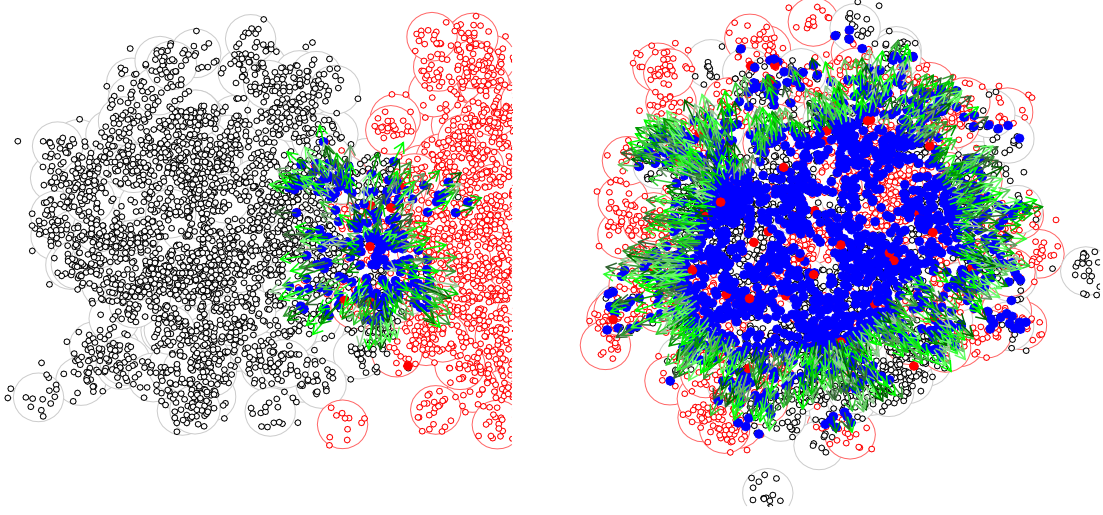

FIGURE 2. Examples of peripheral (left) and central (right) events in MC toy model, with impact parameter $b = 12$ and 0 fm, respectively.

The probability distribution of string boosts β_{string} is shown in Fig.3 (left) for several values of impact parameter b. The shape of distribution changes with b – in more central events, strings in general gain larger boosts. Fig. 3 (right) shows average value $\langle \beta_{string} \rangle$ as function of b for simulations with different string interaction radii R_{string}. For all three radii, some transition region from peripheral to central b can be seen (more "step-like" behavior in case of R_{string}=2 fm), and in more central events $\langle \beta_{string} \rangle$ is nearly constant.

Stage 3. Hadronization of the strings.

Naive hadronization mechanism implemented in this toy model is the following. In its rest frame, each string breaks
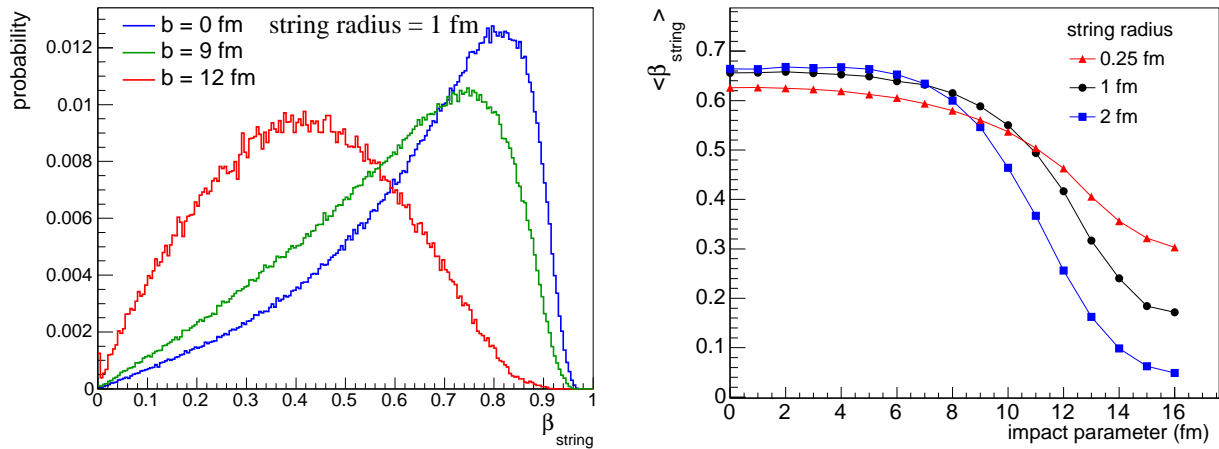

FIGURE 3. String β-boost distribution for different impact parameters.
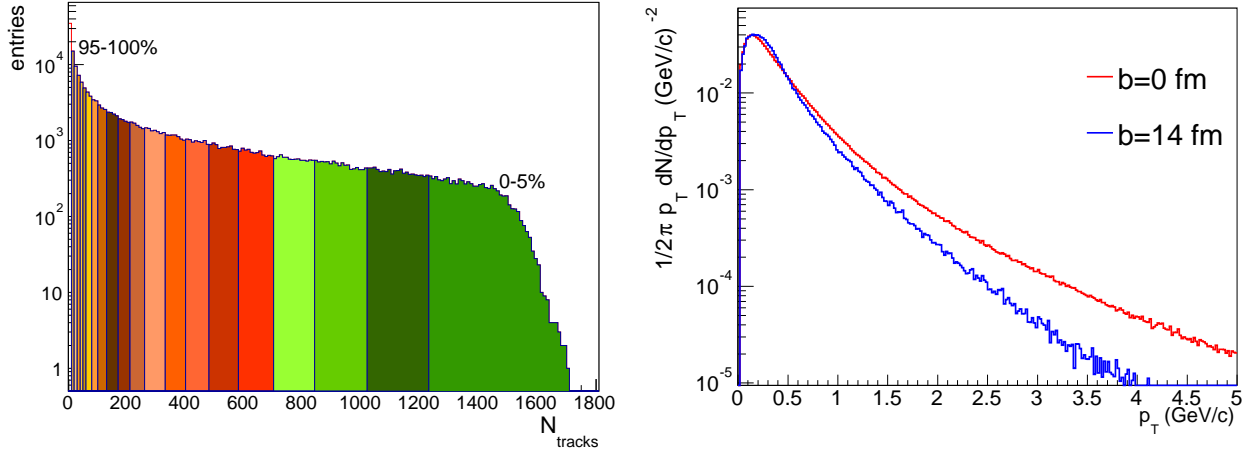
FIGURE 4. Multiplicity distribution divided into 20 multiplicity classes (5% each), obtained in the toy model (left pad). Pions p_T spectra in toy events for two impact parameters $b = 0$ and 14 fm (right pad).

at several points, and in each break-point a pair of quarks appears. The number of break-points is proportional to the string length, with some small random fluctuations. A random transverse momentum distributed exponentially ($\sim e^{-\alpha p_T}$) and random azimuthal direction are assigned to one quark in a pair; the second quark flies out with the same modulus of p_T, but in opposite φ-direction. Each piece of the broken string has two quarks at its ends and is treated as a "particle" (meson). Namely, in this toy model all "particles" originated from the string are assigned to be exclusively ρ-mesons. This assumption simplifies the model, reflecting at the same time the fact that number of ρ mesons in high-energy AA collisions is quite significant. The transverse momentum of ρ is calculated as a vector sum of transverse momenta of its two quarks. The probabilities for the charge of each ρ-meson to be positive, negative or neutral are 25%, 25% and 50%, respectively, and the ρ mass is assumed to be 775 MeV with Gaussian smearing with $\sigma = 80$ MeV. The only decay channels are $\rho^+ \to \pi^+\pi^0$, $\rho^- \to \pi^-\pi^0$ and $\rho^0 \to \pi^+\pi^-$, with the relativistic decay kinematics implemented.

Transverse Lorentz boost β_{string} of each ρ meson is performed at rapidity of $y = 0$. After that, random y, uniformly distributed along the string length, is assigned to this ρ. This approach is quite a rough one, since transverse Lorentz boosts for particles with large $|y|$ should significantly modify dN/dy distribution. However, the distribution of the string boost along y is unknown, thus any reasonable model assumptions are allowed. More sophisticated algorithm of string fragmentation can be found, for example, in the VENUS model [8].

A final state of the event.

The key feature of the toy model is that *in the laboratory frame, all the particles originated from one string are boosted by the factor* $\vec{\beta}_{\text{string}}$. So, in the final state of a toy event, there is a number of π-mesons, which can be "detected".

Fig. 4 (left) shows charged particle multiplicity distribution in pseudorapidity range $|\eta| < 0.5$ obtained in the toy model. In most central events, the multiplicity is ~ 1600, which is similar to central Pb-Pb collisions at LHC at $\sqrt{s_{\text{NN}}} = 2.76$ TeV. As it is usually done in A-A experiments like STAR and ALICE, the multiplicity distribution is divided into "multiplicity classes", which are considered to reflect event centralities. These classes are used below in the event analysis. Right pad of the Fig. 4 shows p_T-spectra of pions in the toy model. The spectra didn't adjusted to fit real data, however, qualitative behavior of the spectra for central and peripheral events is captured.

ANALYSIS OF THE TOY MODEL EVENTS

Dihadron correlations

A set of different observables can be chosen to study consequences of the string repulsion, such as mean transverse momentum p_T, dihadron correlations, harmonic decomposition analysis, etc. As an example, Fig. 5 shows results of dihadron analysis for peripheral and central Pb-Pb collisions, where tracks with $p_T > 0.15$ GeV/c are selected. In

peripheral events, a "ridge"-structure along $\Delta\varphi$ is visible, which is due to the ρ^0 decays. In central events, the well-known away- and same-side ridges, which appear along $\Delta\eta$, can be interpreted as the "elliptic flow" which emerges in the toy system of the repulsing strings. More dihadron results from the MC toy model and the discussion can be found in the contribution called "Constraints on the percolation model from anomalous centrality evolution of two-particle correlations" in the same proceedings.
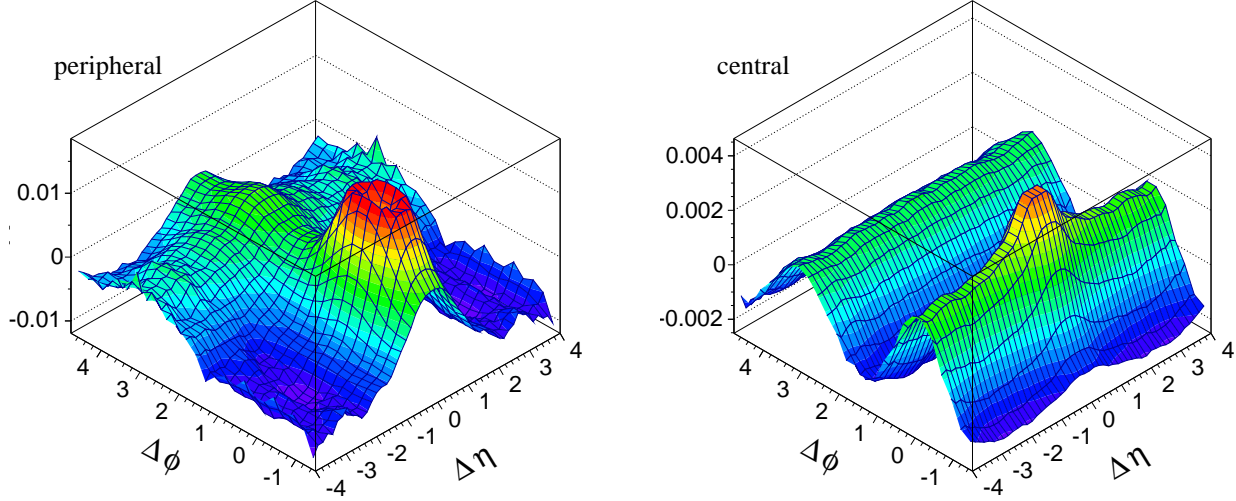

FIGURE 5. Example of dihadron correlation functions obtained in the toy model for peripheral events (left) and for central events (right). The dihadron analysis method, used here, is the same as, for example, in [10]. Charged particles with $p_\mathrm{T} > 0.15$ GeV/c in $|\eta| < 2$ are analysed.

Mean transverse momentum correlations

In the current proceeding, the analysis is focused on long-range correlations obtained with the toy model. The long-range correlations are studied between observables in two different and significantly separated rapidity and azimuthal intervals η_F and η_B, which are conventionally refereed as forward (F) and backward (B) rapidity windows. A correlation coefficient b_corr is defined as the response $\langle B \rangle_\mathrm{F}$ to the deviation of the quantity F from its expectation value $\langle F \rangle$. In this work, quantities B and F are chosen to be *the average transverse momenta* of all particles produced in a given event in, respectively, the backward and the forward pseudorapidity windows:

$$F \equiv \overline{p_\mathrm{T}}_F = \frac{\sum_{j=1}^{n_F} p_\mathrm{T}^{(j)}}{n_F}, \quad B \equiv \overline{p_\mathrm{T}}_B = \frac{\sum_{i=1}^{n_B} p_\mathrm{T}^{(i)}}{n_B}. \tag{2}$$

The correlation coefficient

$$b_\mathrm{corr}^{p_T - p_T} \equiv b_\mathrm{corr} = \frac{\langle FB \rangle - \langle F \rangle \langle B \rangle}{\langle F^2 \rangle - \langle F \rangle^2} = \frac{\langle \overline{p_\mathrm{F}}\,\overline{p_\mathrm{B}} \rangle - \langle \overline{p_\mathrm{F}} \rangle \langle \overline{p_\mathrm{B}} \rangle}{\langle \overline{p_\mathrm{F}^2} \rangle - \langle \overline{p_\mathrm{F}} \rangle^2}. \tag{3}$$

Fig. 6 shows $b_\mathrm{corr}^{p_T - p_T}$ in Pb-Pb collisions in the multiplicity classes of the 5% width (these classes are defined in the left pad in the Fig. 4). The model parameters of the simulation are the same as described before (see Table 1). Forward and backward η-windows are (-0.8, 0) and (0, 0.8), respectively. The values of b_corr are positive and grow with centrality to ≈ 0.4 units for $R_\mathrm{string} = 1, 2$ and 3 fm, while for small radius $R_\mathrm{string} = 0.25$ fm b_corr is significantly lower. One can notice also, that the growth of b_corr with centrality takes off from zero earlier for smaller string radii: for $R_\mathrm{string} = 1$ fm the increase starts already at $\approx 80\%$ of the centrality, while for $R_\mathrm{string} = 3$ fm it happens only at centrality $\approx 50\%$.
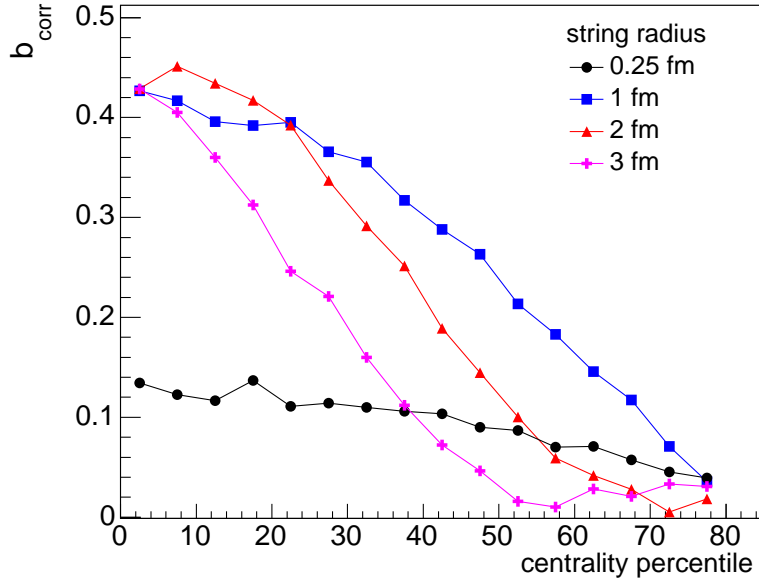
FIGURE 6. Correlation strength $b_{corr}^{p_T-p_T}$ in centrality classes of the width 5%, obtained with the MC toy model for Pb-Pb collisions several values of R_{string} (samples of 500k events each). The FB η-windows are (-0.8, 0) – (0, 0.8), charged particles in p_T range 0.2–2.0 GeV/c are analysed.

Long-range correlations raised due to another possible string interaction mechanism – string fusion - are studied with MC model [5] based on color-dipoles for Pb-Pb [11] and for p-Pb collisions [12].

CONCLUSIONS

The MC toy model for hadron-hadron is built, where quark-gluon strings are formed as a result of partonic interactions inside colliding hadrons, and the string repulsion mechanism is implemented in order to introduce collectivity in the model. The toy model is designed to simulate AA, pA and pp collisions.

Behavior of the model with different parameterizations is explored, it is found that average string boosts in events have a non-linear behavior with centrality and experience saturation for more central events. The analysis of the particular observable – long-range correlations between mean transverse momenta – is presented. Another kind of analysis – dihadron correlations in the toy model – is discussed in separate proceeding in the same volume. The toy model is able to reproduce some experimentally observable features of the azimuthal asymmetry in particle yields. In particular, near-side ridge structure can be obtained.

The model of repulsing strings, however, have difficulties in description of some observations. For example, the strangeness enhancement can hardly be obtained, while it is possible in the string fusion scenario. One can try to unite several string-based models into one to describe experimental data in a more consistent way.

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